Energy Security and Climate Stabilization

Office of Science DOEGenomesToLife.org

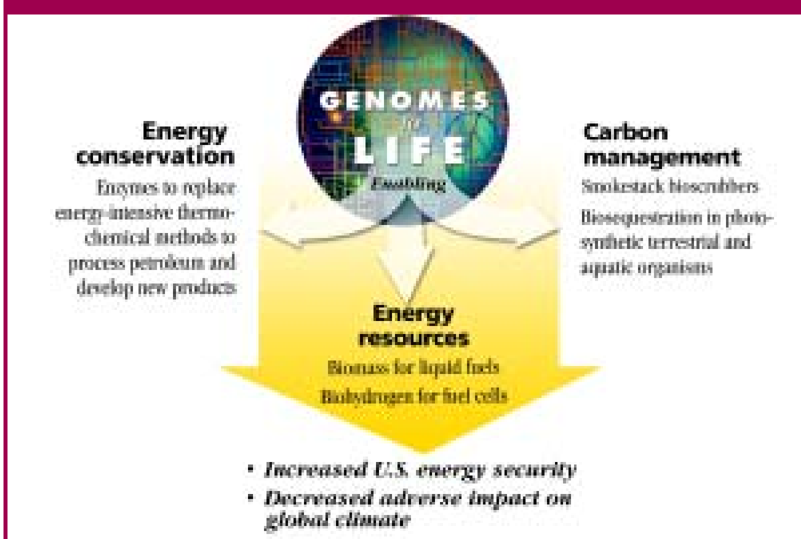
Climate change and energy security, two challenging global issues for the 21st century, are intimately linked. The global energy system is dependent on such carbon-rich fossil feedstocks (raw materials) as petroleum, coal, and natural gas. Yet, emissions from the use of fossil fuels have led to rising concentrations of the heat-trapping greenhouse gas carbon dioxide (CO_2) and the associated impact on global climate. Because carbon dioxide accumulates in the atmosphere rather than being broken down like other greenhouse gases, its concentration will continue to rise unless net global emissions of CO_2 peak and eventually decline to zero. In addition to their environmental impact, fossil fuels are a finite (nonrenewable) resource and often are derived from geographical regions that may be politically unstable. Developing alternatives to fossil resources can provide a more secure energy future and have a significant impact on net CO_2 emissions.

Major oil companies already are moving toward diversifying their products to include renewable and noncarbon-emitting energy technologies. According to Philip Watts, Chairman of Shell, "The next 50 years are not going to be more of the same . . . . There will be different sources of energy by the middle of the century."

The United States is on the path to two complementary goals: increase domestic energy supplies and reduce greenhouse gas emissions. In June 2001, the Bush administration launched the National Climate Change Technology Initiative aimed at accelerating the development of technologies for reducing greenhouse gas emissions. The new U.S. Department of Energy's (DOE) Genomes to Life program also will play an important role in moving the United States closer to its critical energy goals (see below). A brief review of the current U.S. energy system

U.S. Energy Security and Global Climate Stabilization

Complementary Goals



and sources of CO_2 emissions will help explain how the knowledge developed from the Genomes to Life program (see sidebar, p. 7) on understanding genes and protein complexes, their regulation, and their functional roles in an ecosystem can lead both to greater energy security and a stabilization of net atmospheric CO_2 emissions.

U.S. Energy and the Potential Role of Biology

Fossil materials, backbone of the U.S. energy system, are converted to such fuels as gasoline and natural gas for transportation and heat, transformed into chemical products such as plastics, and combusted to produce electricity. Through the use of these products, the United States annually emits 1.5 billion metric tons of carbon in the form of CO_2. Roughly 40% is generated during electricity production and the remainder by the combustion of fuels, including gasoline. Fossil fuels account for 86% of U.S. energy consumption.

In contrast, energy derived from plants (biomass) accounts for just 3% of U.S. energy consumption, mostly a result of the forest products industry's use of wood and pulp residues for process heat. A much smaller portion comes from the 2 billion gallons of ethanol produced for transportation fuel through the fermentation of grain, primarily corn. The use of biomass for energy, often called bioenergy, releases much less net CO_2 into the atmosphere and can contribute ultimately to driving net atmospheric CO_2 emissions to zero. Genomes to Life research findings can lead to applications that will increase the proportion of biomass fuels in the U.S. energy mix.

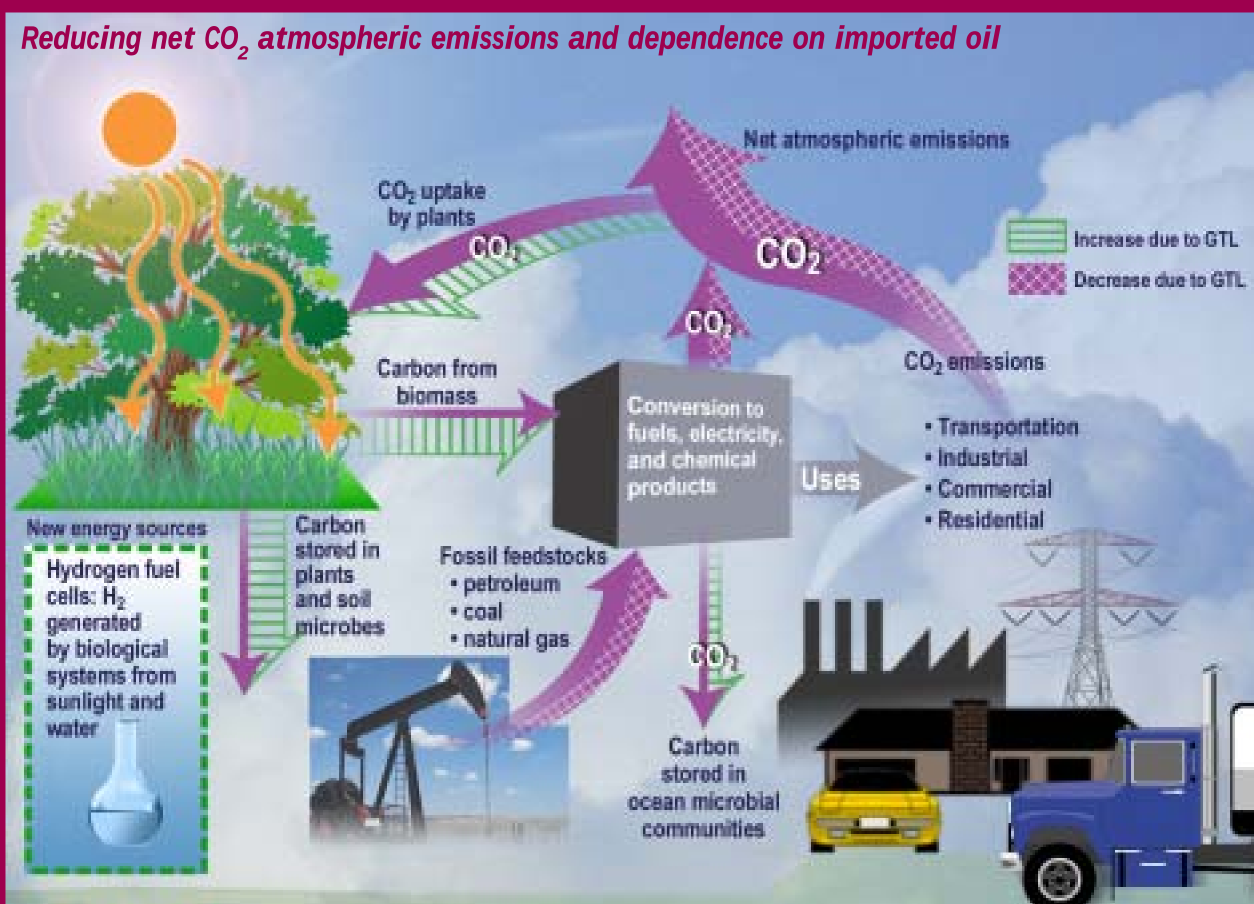
Potential Impact of Genomes to Life on Biomass Production

Plants use the sun's energy to convert atmospheric CO_2 to biomass (e.g., leaves, roots, stems, seeds) composed mainly of cellulose and lignin. Some biomass ultimately becomes incorporated into the soil where its carbon may be sequestered for hundreds of years. The harvested portion above ground can be used for the same purposes as fossil feedstocks—fuel and electricity. When biomass products are used, carbon is transformed back to CO_2 and taken up again by a new generation of trees and grasses. Thus, net carbon emissions from using energy generated by biomass feedstocks are potentially close to zero, especially if carbon is also sequestered in the soil (see figure, p. 3). In the short term, producing more biomass feedstocks on U.S. land can reduce net carbon emissions, decrease climate impact, and enhance the nation's energy security.

The profound understanding of genes, protein complexes, and their regulation obtained in Genomes to Life can have a significant impact on the ability to increase biomass feedstocks, whose amount and composition are controlled by genes (see figure, p. 4). Genomes to Life seeks to understand how genomes work, allowing scientists to predict how cells respond to different environments. Obtaining this deep level of knowledge requires a fusion of experimental biology and advanced computing. Data must be assimilated, understood, and modeled on the scale and complexity of real living systems and processes. Understanding plant genes and their regulation ultimately will enable manipulation of carbon storage and thus plant productivity. These advances also will allow control over the allocation of carbon to above-ground components that can be harvested for energy or below-ground components that can sequester carbon in the soil. Perhaps just as important, feedstocks can be tailored to the products desired. If ethanol is the desired product, for example, lignin content could be reduced and plant cellulose and starch content enhanced. People have been manipulating plant genomes since the beginning of agriculture. New biotechnological capabilities will allow far greater efficiency and precision in these tasks. Advances also will enable explorations into the interplay of plant and microbial genes in regulating nutrient availability and uptake. Future scientists will be able to design plant-soil-microbe systems to optimize growth for specific soils and climates.

Biomass crops are well poised to take advantage of advances offered by biotechnology. The rapidly growing, easily cloned poplar (*Populus*) tree is an excellent model to consider. For production on well-watered rich lands, for example, a sterile and stubby type of tree could be designed with high cellulose content (providing biomass for conversion to fuels and fiber), fibrous roots, and high pest resistance. Because of its potential as feedstock for bioenergy, a poplar project was launched by an international group of scientists at universities and DOE national laboratories in 2002 to determine the DNA sequence of its genome (see sidebar, p. 4). These data will provide the basis for future genetic understanding and manipulation. Because different plant species contain many similar genes, genetic knowledge of other plants also can serve as a guide for regulating relevant poplar genes.

Genomes to Life: Potential Impact on CO_2 Emissions



Enhancing Plant, Microbial Traits for Energy Applications

Payoffs:

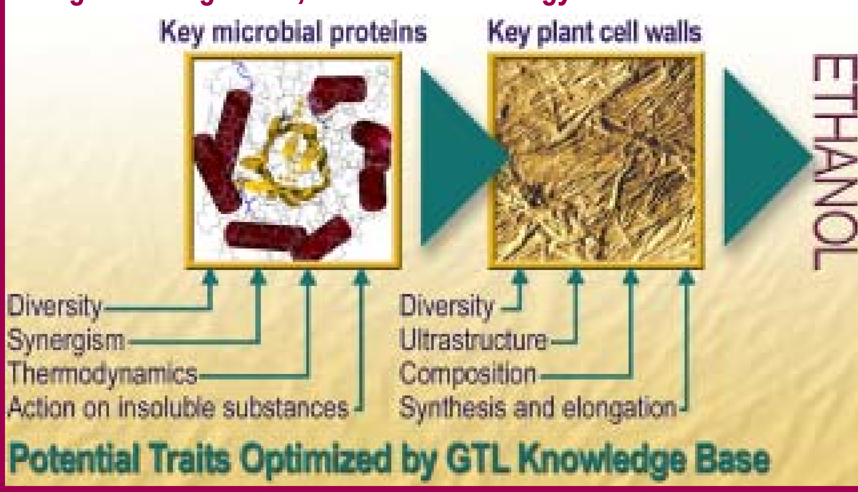
- Greater carbon storage ability to help reduce net atmospheric CO_2 and global climate change
- Enhanced production of biomass-derived fuels to displace a significant amount of imported oil
- Creation of domestic jobs in biomass production and conversion

In 2002 a poplar genome project was launched by an international consortium of scientists at universities and DOE national laboratories. The knowledge of the interactions between genes and protein complexes obtained from the Genomes to Life program, combined with the catalog of genes that control important functions generated by the poplar sequencing project, will provide the basis for future understanding and enhancement of trees for DOE energy and environmental missions.

Vision for the future: A domesticated poplar tree modified to yield more energy- and cost-efficient products such as ethanol

- Compact crown and root system
- Optimal allocation to biomass components
- Higher harvest efficiency
- Higher productivity per unit area
- Greater product yield per tree
- Non-flowering

Enhanced plant qualities and microbial bioprocesses for generating clean, sustainable energy



Microbial cellulase protein "machines" can be used to break down cellulose in plant cell walls. Today, the process is too inefficient for commercial ethanol production. Fundamental knowledge of plant and microbial processes gained in Genomes to Life can be applied to develop more efficient methods.

The Switch to Bioenergy: Potential Major Payoffs

- **Independence from the gasoline produced from imported oil**
- **Major reduction in net atmospheric CO_2 emissions to counter global warming**

Within 25 years, advances in understanding gene function and regulation could enable both a doubling of U.S. bioenergy crop yields and a significant increase in the efficiency of converting biomass to ethanol. These advancements could significantly reduce both U.S. dependency on foreign oil for gasoline and net CO_2 emissions, while simultaneously improving the economic and environmental health of rural areas in the United States.

A joint DOE and U.S. Department of Agriculture study has shown that doubling yields from bioenergy crops would enable the economic conversion of 55 million acres of U.S. cropland to bioenergy crop production (e.g., switchgrass, hybrid poplar, and willow) with little impact on food production. Combining these increases in energy crop yields with expected improvement in ethanol yields from biomass could lead to the production of 900 gallons of ethanol from biomass harvested on one acre of cropland. Under this scenario, 50 billion gallons of ethanol could be produced annually from U.S. cropland.

Fifty billion gallons of ethanol is sufficient to satisfy 25% of projected 2020 U.S. gasoline needs. This production would increase biomass use from the current 3% of total primary energy use to 6% of projected 2020 primary energy use. Assuming the ethanol is used in an E85 blend (15% gasoline; 85% ethanol) and taking a full life cycle approach to calculating CO_2 emissions,* the dedication of 55 million acres of U.S. cropland to bioenergy crops used to produce ethanol would result in an annual avoidance of 406 million metric tons of CO_2 or 111.4 million metric tons of fossil carbon emissions. From an energy security perspective, with these enhanced crop and ethanol yields, bioenergy crop production from only 39 million acres could provide enough biomass for ethanol production to displace all projected 2020 oil imports from the Persian Gulf used to produce gasoline.

Additional positive environmental and economic impacts that can occur with the use of ethanol produced from bioenergy crops include decreased chemical and herbicide use for bioenergy crops relative to traditional crops. Furthermore, with appropriate management practices, erosion and chemical runoff can be reduced relative to traditional crop production. Farm income increases with bioenergy crop production (estimated to be in excess of $6 billion annually). Moreover, estimates are that for every billion gallons of annual ethanol production, there is a $1.35-billion economic impact including 6,000 jobs resulting just from plant operation. This latter impact results from ethanol plant operation only, and multiplier effects would increase the total expected economic impacts.

*A life cycle approach accounts for CO_2 emissions associated with all aspects of producing and using ethanol or gasoline.

Enhancing Biological Conversion to Useful Products

Genomes to Life is developing a basic knowledge base that will be applicable to all living systems. Advances from the Genomes to Life program will lay the foundation for designing ways to put the biological abilities of various organisms to work, for example, in converting biomass and even fossil materials to a vast array of chemicals and other products. Microbes—nature's simplest and most abundant organisms—have evolved for some 4 billion years and offer a deep and untapped resource of capabilities. Although people have been using microbes such as yeast for millennia to make bread rise or ferment sugars into alcohol, the process of identifying and harnessing the enormous array of microbial capabilities is just beginning.

The understanding gained across protein complexes, microbes, and microbial communities will lead to the ability to enhance microbial conversion capabilities. This enhanced conversions of substances will enable new products (e.g., biopolymers and hydrogen) and better processes (e.g., low-energy paper production and biodesulfurized diesel fuel). These applications will improve energy security by replacing petrochemical use with biobased processes and through the use of energy- and waste-efficient processes.

Companies including DuPont and Cargill Dow already are establishing manufacturing facilities to supplement products derived from fossil material with new biopolymers from biofeedstocks (plant biomass). DuPont expects 1-3 propane-diol to be its next nylon, and Cargill Dow views polylactic acid as a potential replacement for polyethylene.

Currently, petroleum refineries "crack" raw oil through heat and catalysis to create gasoline and other petroleum products. In the future, biorefineries could use microbial cellulase enzymes to crack the complex cellulose and hemicellulose in plant walls into simple sugars. These sugars could then be microbially fermented into ethanol and other biobased products. Genomes to Life research findings can accelerate this vision by improving the understanding of both plant cell-wall construction and the microbial enzymes necessary to deconstruct those walls (see figure, p. 4). This knowledge could one day lead, for example, to creation of a bioengineered poplar tree with a thermocellulase in its wood that is expressed only at high temperatures: a biofeedstock designed for self-disassembly when exposed to intense heat. The discovery or creation of a microbe that could ferment sugars at high temperatures or high ethanol concentrations would vastly improve the efficiency of the bioethanol process. These are just a few examples of where a fundamental understanding of genes, their enzyme (protein) products, and their regulation could lead.

Microbes also could play a role in increasing and improving the quantity and quality of domestic fossil fuels. These organisms can convert synthetic gas derived from coal to liquid fuel such as ethanol. Microbes already are being added to thin the oil in wells and permit pumping of petroleum that otherwise would be too thick to extract. Through similar processes, they could increase the recovery of oil from shale in the western United States.

The ability to manipulate and harness genomes will also create new opportunities to design novel bioprocesses that can "save" energy by eliminating current energy-intensive processes. For example, microbial desulfurization (the

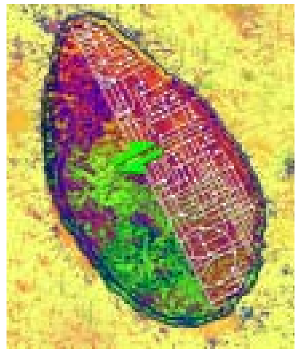
Genomes to Life Program

DOEGenomesToLife.org

DOE Office of Science

DOEGenomesToLife.org/energy

Systems Biology for DOE Missions

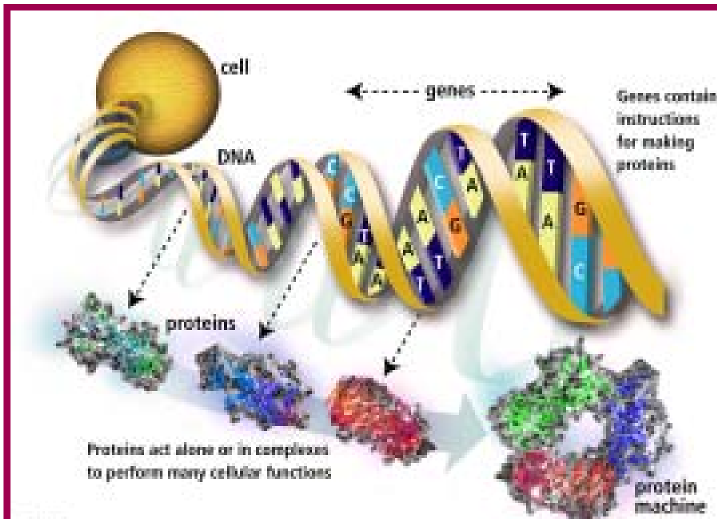


The new Genomes to Life program focuses on leveraging information obtained from genome sequences to achieve a fundamental, comprehensive, and systematic understanding of life. The program has four major goals:

- Understand how protein complexes work together as cellular machines to accomplish the "work" of life (e.g., energy capture, movement, growth, and reproduction)
- Understand gene regulatory networks that regulate the expression of enzymes and other proteins (i.e., timing, quantity, duration, and type)
- Understand how diverse species of microorganisms work together (through genes, proteins, and other molecules) in the natural environment
- Develop computer tools to process, understand, and make predictions from the massive amounts of raw data contained in genes and associated proteins and regulatory networks

Genomes to Life seeks to understand the interactions of genes (the instructions) and proteins (the machines). The program will provide a strong underpinning of knowledge on how genes and proteins function together—as protein complexes (cellular machines), as a network within a cell, and within a diverse community of life forms. Over billions of years, under a wide variety of environments, the process of evolution has resulted in organisms that are capable of splitting water into hydrogen and oxygen, converting CO_2 into sugar, breaking apart complicated and even toxic chemicals, producing valuable chemicals (e.g., ethanol), or "sensing" certain chemical compounds. The fundamental knowledge from Genomes to Life is key to enabling us to efficiently and effectively harness this incredible array of capabilities.

Genomes to Life moves beyond traditional biology approaches, which focus on single components in isolation, to a "systems biology" approach, which explores complex interactions of many levels of biological information simultaneously. The knowledge gained from Genomes to Life will help mission-targeted research programs attain their specific goals more efficiently and more effectively.



replacement of sulfur-carbon bonds with hydrogen-carbon bonds) of oil could replace the energy-intensive thermochemical methods now used to desulfurize petroleum. These processes would reduce costs and increase the amount of usable energy from a barrel of petroleum.

Finally, in the next quarter to half century, further advances may lead to large-scale production of hydrogen gas for fuel cells and the ability to store in the ground both bio- and fossil-derived CO_2. Microbes could enable the inexpensive production of hydrogen by consuming a hydrogenated feedstock and releasing H_2, for example, splitting water with light or splitting hydrogen from biomass or even coal. The hydrogen could then be used in a broad array of energy applications. Because the combustion by-product of hydrogen is water vapor, hydrogen could provide an end-use energy carrier, which would have no direct greenhouse gas emissions. In addition, hydrogen is attractive because it is portable and could be used in the transportation sector. If the origin of the hydrogen were biomass and if the by-product carbon emissions were captured and stored, we could actually produce energy and absorb CO_2 from the atmosphere at the same time. Implementing a combination of technologies that contribute to reducing net CO_2 emissions will move the nation toward the ultimate goal of zero net emissions.

The future lies in environmentally sustainable, secure energy sources. Skillful, targeted application of biotechnology based on understandings gained through such basic research programs as Genomes to Life will make genes, their regulation, and their protein products an important pathway to this future.

Photomicrograph, p.7: M. A. Bruns and Center for Microbial Ecology, Michigan State University

U.S. Department of Energy Office of Science

Marvin Frazier
Office of Biological and Environmental Research (SC-72)
301/903-5468, Fax: 301/903-8521
marvin.frazier@science.doe.gov

Gary Johnson
Office of Advanced Scientific Computing Research (SC-30)
970/225-3794, Fax: 970/223-1415
garyj@er.doe.gov

Office of Science: www.sc.doe.gov
Genomes to Life Program: DOEGenomesToLife.org